EVALUATION OF RECLAIMED ASPHALT PAVEMENT AND RECYCLED CONCRETE AGGREGATE AS A DENSE GRADED AGGREGATE BASE COURSE

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16. Abstract

This report documents the laboratory and field study of reclaimed asphalt pavement and recycled concrete aggregate for use in base course. The study was conducted to confirm the recently adopted RAP specifications, and investigates the engineering properties such as gradation, degradation, resilient modulus and permanent deformation of RAP, RCA and blended 75% dense graded aggregate with 25 % RAP, and compares these properties with DGA. Four base course projects with RAP, RAP/DGA blend, and DGA for comparison were constructed to investigate and confirm the constructability, density, and rutting potential. The use of 100% RAP base course in-place of dense graded aggregate is confirmed for low and medium traffic pavements. Since RCA has been used successfully for several years as base course, no test projects were constructed to confirm the use of RCA base course. The use of RAP/DGA blend is also confirmed for use in base course.

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INTRODUCTION

Objective

The objective of this study is to determine the engineering properties and field performance data for reclaimed asphalt pavement (RAP) and recycled concrete aggregate (RCA) for dense graded aggregate base courses. Using these data, the study will develop guidelines and a modified specification for the use of these materials in dense graded aggregate base courses.

The laboratory testing includes gradation analysis, debonding analysis, density, California Bearing Ratio and resilient modulus tests. Permanent deformation of samples is calculated from the resilient modulus tests to analyze the potential for pavement rutting. An analysis is performed of the AASHTO and NJDOT California Bearing Ratio test methods. The field performance testing includes experimental test sections on four construction projects: (1) US Route 206 Maintenance shoulder reconstruction, (2) Cedar Lane, Piscataway Local reconstruction project, (3) US Route 1, Section 5G & 6U, New Brunswick reconstruction and widening, and (4) US Route 46 Maintenance shoulder reconstruction. The field test sections were analyzed with the Heavy/Falling Weight Deflectometer, the Seismic Pavement Analyzer, and ARAN rut depth measurements.

Background

The stockpiled millings from bituminous pavements and crushed concrete from PCC pavements and highway structures are a continuing problem for the highway construction industry. present method for dealing with pavement millings, called reclaimed asphalt pavement (RAP), is to stockpile the material for limited use in both bituminous concrete for pavements and dense graded aggregate base courses. The crushed concrete, called recycled concrete aggregate (RCA) is also stockpiled for use in base courses. Dense graded aggregate has been produced from

recycled concrete aggregate for several years. The constructability of RCA has been proven by numerous successful base course projects.

The present specification for RAP in bituminous concrete allows up to 10 % RAP in surface course and 25% RAP in bituminous stabilized base from stockpiled material sources (Open System), and up to 50% RAP from the ongoing milling and paving project (Closed System).

The NJDOT's present policy for overlay construction is to mill off 50 mm of the pavement and replace with 50 mm or 100 mm of bituminous concrete. The overlay can use up to a maximum 50% of the milled pavement which requires stockpiling the remaining material. This valuable stockpiled material can be used in aggregate base course.

The NJDOT allows the production of dense graded aggregate with RAP under a recently revised specification. The dense graded aggregate base course mixtures can be produced with up to 100% RAP as long as it meets a specific gradation. This revised Dense Graded Aggregate specification includes a provision for Determination of Gradation of Dense-Graded Aggregate Containing Reclaimed Asphalt Pavement, as shown in Appendix A & B.

Using 100% RAP base course could effectively eliminate the large stockpiles of this material. Pavement designers and the construction industry have been reluctant to use the 100% reclaimed asphalt pavement mixture because it does not meet the gradation aforementioned requirements and because laboratory and field data are not available on material characteristics and rutting performance. This study addresses the need for specification confirmation, engineering properties of both RAP and RCA, and field constructability projects of the use of RAP as dense graded aggregate in base course.

RESEARCH APPROACH

A literature search was conducted to provide a source of existing information on the use of recycled materials in pavement systems. The literature search addressed the development of specific design parameters for RAP such as gradation or using the current design parameters of dense graded aggregate base course (DGABC) to define base courses using the recycled materials.

The laboratory testing was conducted to characterize the geotechnical properties of the recycled and reference virgin base materials. The laboratory tests include material classifications, gradation analysis, compaction characteristics, degradation analysis, CBR analysis, and permeability characteristics. The resilient modulus data were determined for the recycled and reference virgin base materials. The test parameters include material type, compaction characteristics, bulk or confining stress, and load patterns

To evaluate the constructability and rutting, the RAP materials were constructed in base course field projects, and compared to virgin DGA base course in the same project. The experimental base courses were constructed with 100% RAP mix and the blended 75% DGA and 25% RAP mix. The RCA base course was compared with the RAP and DGA base courses. The material properties such as density and gradation of the in-situ materials were determined for evaluation of the construction techniques, rutting and development of specifications. The typical in-situ stiffness modulus values were determined by using both deflection based Heavy/Falling Weight Deflectometer (FWD) and wave propagation based (SASW) nondestructive testing methods. The rutting measurements were made with an Automatic Road Analyzer (ARAN). The results of the laboratory tests and field tests were used to develop the specifications and recommendations for implementation of the RAP materials.

LITERATURE SEARCH

The limited use of recycled concrete aggregates in base and subbase materials, and related laboratory investigations is documented in the literature. O'Mahony and Milligan (1) conducted California bearing ratio, shear box and frost susceptibility tests on RCA for subbase layers. CBR tests indicated that the RCA was found to be similar to that of crushed limestone. shear box tests indicated that the RCA could be classified as a medium-strength subbase aggregate. The frost susceptibility tests indicated that the RCA falls into the range of frost susceptible.

Barksdale, Itani, and Swor (2) performed repeated load triaxial tests to evaluate resilient modulus and rutting potential, CBR tests, Los Angeles degradation and gradations to define aggregate breakdown under compaction and repeated loading conditions. The resilient modulus tests showed that the RCA would be expected to have similar values to the Minnesota sand and gravel blends. With respect to rutting and permanent deformation, the recycled concrete was slightly more susceptible to permanent strain than the dolomite base but performed comparably with the dolomite for rutting . In the CBR tests, the recycled concrete performed as well as or better than the comparable dolomite base. The recycled concrete showed significant degradation of particles as compared with the dolomite.

After investigating the use of RAP in subbase layers, Davis, Huston, and Lee (3) concluded that 100 % RAP may be more appropriate for the base layer than the subbase layer due to the RAP's high strength. The investigation included RAP materials from six new England States and tested the materials for gradation, moisture-density relations and resilient modulus. The mixtures of gravel, RAP and Portland cement have higher resilient modulus values than the granular material, and the 100% RAP had the highest resilient values of all materials in the test.

Garg, and Thompson (4) conducted a study to determine the potential for the application of RAP as a pavement base layer. The study includes construction and laboratory testing of RAP base course, and compares the results with the standard dense graded crushed stone aggregate base. Gradation tests showed that the RAP gradation differs from the dense graded aggregate base specification on the - 4.75 mm and the - 75 μm values. The gradation difference is attributed to the tendency of the fines to cling to the larger RAP particles. The triaxial testing for resilient modulus and permanent deformation data was performed to determine engineering properties of the RAP and crushed aggregate. The resilient modulus values of the RAP were higher than the crushed aggregate, and the permanent deformation values indicate a high potential for rutting of the RAP base course material. The construction testing indicated that no fatigue or transverse cracking was observed on the sections, and the RAP rutting potential was not confirmed in the test. The study concluded that RAP can be successfully used as a base course material.

LABORATORY TESTING

Gradation Analysis

The reclaimed asphalt pavement (RAP) samples for the laboratory testing were obtained from an approved stock pile for the US Route 1, Section 5G & 6U project which is located in New Brunswick, New Jersey, and Trap Rock Industries, Kingston, New Jersey. The dense graded aggregate (DGA) and the RAP for the blended 75% DGA and 25% RAP mix was obtained from an approved stock pile at Trap Rock Industries. The recycled concrete aggregate (RCA) was obtained from an approved stock pile at Stavola Construction Company.

The gradation analyses were performed on sampled materials according to AASHTO Designation T 27-93. The gradation analyses of the laboratory test samples for the resilient modulus and permanent deformation tests are compared to the NJDOT RAP and DGA specification, and are shown in Table 1 The gradation analyses show that the 100% RAP US Route 1 sample does not meet the RAP gradation specification on the 4.75 mm sieve and the 300 μm sieve, and the RAP Trap Rock sample does not meet the specification on the 19.0 mm sieve. The DGA sample and the RCA sample do not meet DGA gradation specification on the 75 μm sieve. Although the DGA Trap Rock and RCA Stavola samples do not comply completely with the virgin gradation specification, it was determined that they were sufficiently acceptable for the purposes of this investigation.

Density

The maximum laboratory dry densities and moisture contents of the RAP, DGA, Blend 75% DGA/25% RAP and RCA were performed according to AASHTO T 99-94. The average density and moisture are shown in Table 2.

Table 1: Gradation Analysis of Laboratory Samples and comparison to NJDOT Specifications

			(Percent Passing)				
Sieve Size	RAP Gradation Specification	DGA Gradation Specification	RAP US Route 1	RAP Trap Rock	DGA Trap Rock	Blend DGA/RAP Trap Rock	RCA Stavola
50.8 mm	100		100				
37.5 mm	85-100	100	93	100	100	100	100
19.0 mm	55- 90	55- 90	66	95	81	77	70
4.75 mm	25- 60	25- 60	16	60	31	43	30
300 μm	3 - 25	5 - 25	1	3	7	10	5
75 μm	0-10	3-12	0	<1	2	5	<1

Table 2-Comparison of Laboratory Sample Moisture Density Relationships

Material	Maximum dry density (kg/m^3)	Optimum Moisture Content (%)
RAP- US Route 1	1810	5.5
RAP -Trap Rock	1861	5.0
DGA	2098	7.0
Blend 75% DGA/25% RAP	2056	7.0
RCA	1907	6.0

Material Degradation

The asphalt binder in RAP has the potential to debond with large aggregate and to bond with smaller aggregate. To evaluate this characteristic, sieve analyses were performed before and after compaction tests to determine if any degradation had occurred during the compaction process. The compaction tests were performed in accordance with the moisture density relationships of soils, AASHTO Designation T99-94. As the results show in Figure 1, a slight degradation has occurred between 38 and 13 mm size grains, however, grains between 13 and .03 mm bonded together during compaction. The degradation of the larger particles may be attributed to the debonding of the aggregates from the asphalt binder.

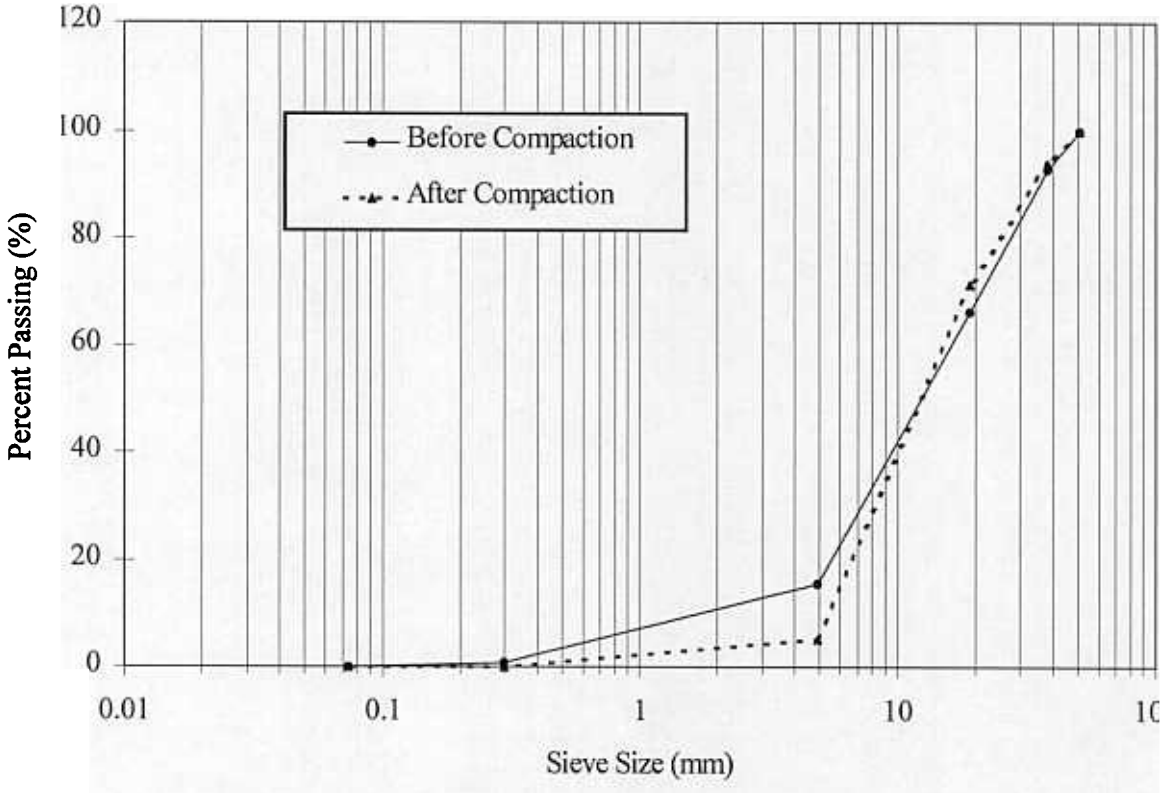


Figure 1. Gradation of reclaimed asphalt pavement before and after compaction

Accelerated RAP Drying Tests

The accelerated RAP drying tests were conducted to develop a procedure to reduce the drying time of RAP samples without significantly altering the gradation of the material. Oven drying was selected to simulate the standard air drying process.

Five samples of an approved stockpile were obtained from the Trap Rock Industries, Kingston, NJ plant. Each sample of 14.5 kgs was split and designated "A" or "B" to facilitate the testing.

The "A" samples were weighed, spread out on the floor one layer deep, and air dried for 24 hours. The sample gradation was performed according to standard procedures and the moisture content calculated for each sample. The accelerated drying test results are shown in Table 3.

The "B" samples were each weighed, divided into two pans to spread the material, and placed in a preheated oven for five hours at 82.2 degrees C. The material was removed from the oven once every hour and mixed to promote even and thorough drying. After drying, a gradation was performed and the moisture content calculated for each sample.

A statistical test of the significance of the gradations differences was calculated for Sieve Sizes: 19.0 mm, 4.75 mm, 300 μm, and 75 μm. The hypothesis test of the means of paired samples was conducted to determine any significant difference in the sample gradation between the standard drying method and the oven drying method. The paired t-test results are shown in Table 4. Using a 95% confidence level, the results indicate that the RAP gradations were significantly affected by the oven drying method on the 300 μm, and 75 μm sieve sizes. The gradation was nearly significant at the 4.75 mm gradation and was not significant at the 19.0 mm gradation.

Table 3. Accelerated RAP Drying Tests

Air - Dried Samples						
	Percent Passing (%)					
Sieve Size	Sample 1A	Sample 2A	Sample 3A	Sample 4A	Sample 5A	Average
50.8 mm	100.0	100.0	100.0	100.0	100.0	100.0
37.5 mm	100.0	100.0	100.0	100.0	100.0	100.0
19.0 mm	86.1	85.4	84.2	81.5	88.6	85.2
4.75 mm	36.1	36.4	39.5	38.0	42.8	38.6
300 μm	4.6	4.8	4.5	4.5	5.0	4.7
75 μm	0.7	0.7	0.6	0.6	0.6	0.6
Percent Moisture (%)	2.66	2.47	2.59	2.84	2.68	2.65

Oven - Dried Samples						
	Percent Passing (%)					
Sieve Size	Sample 1B	Sample 2B	Sample 3B	Sample 4B	Sample 5B	Average
50.8 mm	100.0	100.0	100.0	100.0	100.0	100.0
37.5 mm	100.0	100.0	100.0	100.0	100.0	100.0
19.0 mm	83.9	82.0	82.6	87.3	84.0	84.0
4.75 mm	34.3	30.0	38.5	38.3	38.3	35.9
300 μm	2.7	2.5	2.5	2.6	2.5	2.6
75 μm	0.3	0.3	0.2	0.2	0.2	0.2
Percent Moisture (%)	2.96	2.95	2.45	3.36	3.32	3.01

California Bearing Ratio Tests

The California Bearing Ratio (CBR) is a test method used to evaluate the potential strength of subgrade, subbase and base course material, including recycled materials for use in road and airfield pavements. The CBR value obtained in this test forms an integral part of several flexible pavement design methods.

The CBR tests were performed by two different methods. The first method was performed in accordance to AASHTO T193-93, and the second was performed in accordance to the NJDOT method which is shown in Appendix C. For both methods, a computer program was written to advance the penetration piston 1.27 mm per minute to the penetration piston, until a penetration depth of 12.7 mm was reached. The load and stroke were recorded every 0.635 mm. A data analysis program was written to perform the necessary calculations to determine the CBR values at 2.54 and 5.08 mm penetrations.

AASHTO T 193-93 method

The sample is prepared from all material passing the 19 mm sieve. The mold and extension collar were clamped to the base plate and weighed. The representative sample of material was weighed and mixed with water to achieve its optimum moisture content. The material was then placed in the mold and compacted in three equal layers with 56 blows per layer, as specified by AASHTO T 99. Moisture samples were obtained and determination of moisture content was evaluated in accordance with AASHTO T 265, Laboratory Determination of Moisture Content of Soils.

The compacted sample was trimmed even to the top of the mold and the extension collar was removed. The mold and compacted specimen were weighed to determine the density before running the test.

NJDOT Method

The sample is prepared as above and is separated by sieve size and the moisture density test is performed by AASHTO T-99. The manufactured 4000 gram sample is placed in the CBR mold with the spacer disk on the top of the material. The sample is compressed in a universal compression machine with a load of 25,400 kilograms.

CBR Results

The CBR values are shown for both methods in Table 5. The results show a large variability between the methods and a large variability between the samples within each method. The variability of CBR values of the AASHTO method may be affected by the debonding of the grains from the asphalt binder. In the NJDOT method, the high values may be attributed to the compaction by static loading which compacts samples to densities above the maximum density. For this reason, the CBR values for NJDOT method were typically 100 to 700 % higher than the AASHTO method.

Table 5. California bearing ratio results

Material/Source (Laboratory Samples)	Test Method - CBR Value Range			
	AASHTO T-13		NJDOT Method	
	2.54 mm pen.	5.08 mm pen.	2.54 mm pen.	5.08 mm pen.
RAP US Route 1	9 -17		100 - 110	
RAP Trap Rock	13 - 22		105 - 115	
DGA		40 - 70		75 - 150
RCA		50 - 85		100 - 150

Resilient modulus

Resilient modulus is an index that describes the nonlinear stress-strain behavior of soils under repeated loads. Mechanistic procedures for design of pavements and overlays require resilient modulus values for determining layer thickness and the overall system response due to traffic loads. The resilient modulus test provides a basic constitutive relationship between stress and deformation of pavement construction materials for use in structural analysis of layered pavement systems.

The Resilient Modulus (M_r) is defined as the ratio of deviatoric stress to the magnitude of recoverable strain for a given loading sequence. The critical resilient modulus testing parameters are those associated with the loading magnitude and sequence, i.e., deviatoric stress, confining pressure, and number of cycles. The resilient modulus for each stress state was evaluated as follows:

$$M_r = \sigma_d / \varepsilon_r$$

where

M_r = resilient modulus,

σ_d = applied deviator stress, and

ε_r = recoverable strain.

The accumulation of permanent deformation in subbase and base will contribute to surface deformations, resulting in rutting and cracking. Typically, resilient modulus is emphasized more than permanent deformation when describing geotechnical parameters of a base material. However, when dealing with rutting potential, permanent deformation tests may be more informative, since resilient modulus tests only describes the modulus at various stresses.

Resilient modulus does not give an indication of the permanent deformation during the test, however permanent deformation at 1500 cycles can be extracted from the data obtained from a resilient modulus test. In this study, the samples were subjected to 100,000 axial repetitions of 310 kPa at a confining stress of 103 kPa.

The testing apparatus is an MTS Model 810 with Teststar II Data Acquisition and Control System. The loading system consists of an eight foot loading frame and closed loop servo controlled hydraulic actuator . The loading frame has a movable cross head to allow for easy placement and removal of test specimen. A 100 kN servo controlled actuator is mounted on the movable cross head with a 25 kN load cell to measure the applied load.

A triaxial chamber capable of testing specimens with a diameter of 152 mm and a height of 304 mm was used to meet the requirements of AASHTO specification T 294-92. The top plate of the chamber was modified to hold a pressure transducer, used for measurement of confining pressure within the chamber, and two LVDT'S. The two LVDT's were used to measure axial deformations of the specimen. The schematic of the triaxial cell and the system is shown in Figure 2.

The computer controlled system was programmed to acquire data from two external LVDT's, load cell and a chamber pressure transducer every time a maximum and minimum load was recorded by the load cell during the 0.1 second haversine load cycle during the resilient modulus and permanent deformation tests.

Sample preparation followed that of AASHTO Designation T 294-92 type 1 soil. A representative sample of material was weighed and mixed with water to achieve optimum moisture content. A vacuum was applied to the split mold to insure the membrane was drawn

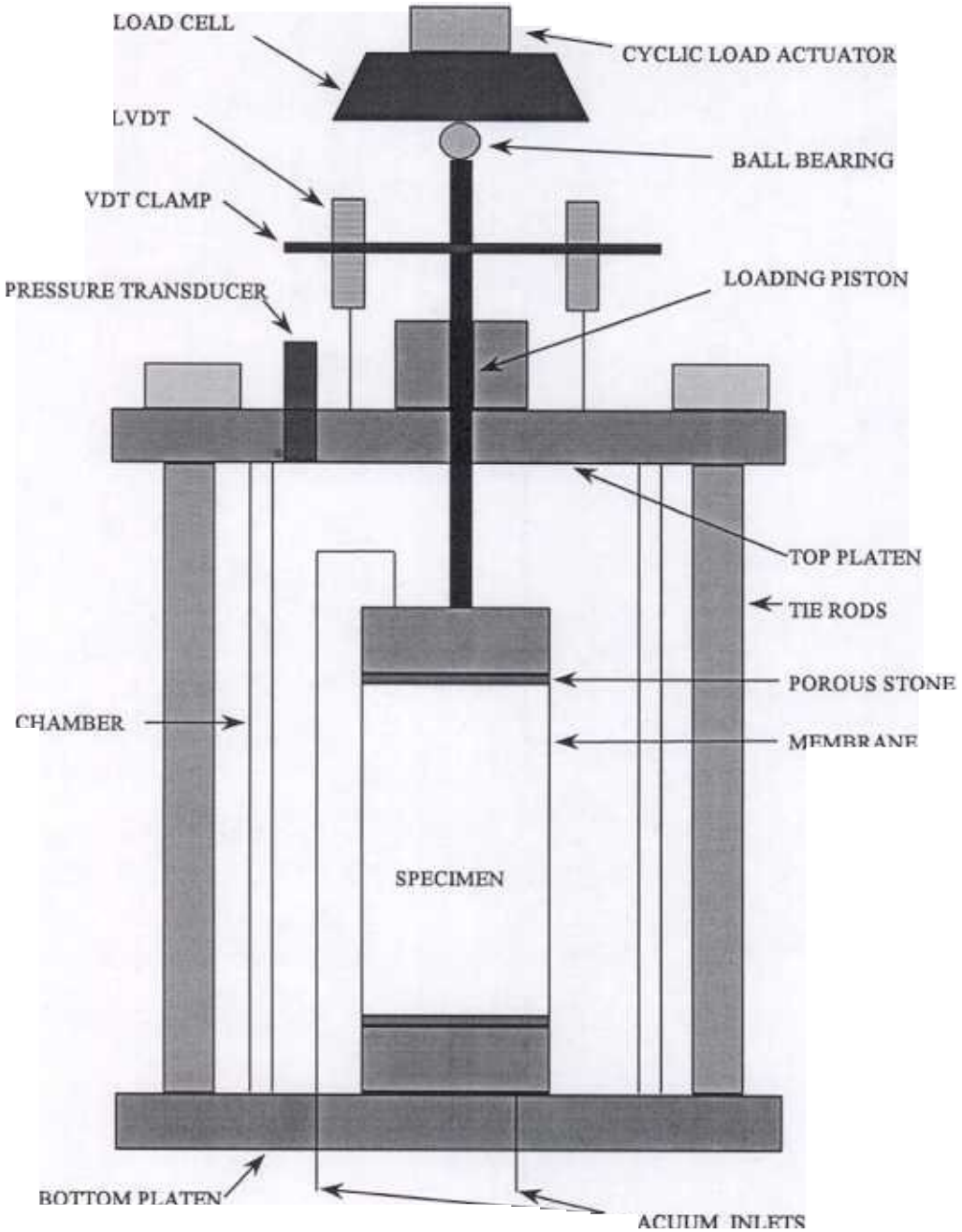


Figure hemati of the triax al cel and system

tightly to the inner surface of the mold, and placed over the bottom porous stone and platen. Five equal layers of soil were placed in the mold and compacted using a custom vibratory device. The compaction device consisted of a vibratory demolition hammer attached to a rod with a steel compaction plate 146-mm in diameter and 12-mm thick. The compaction device was equipped with a soil layer thickness gage. This layer thickness gage alleviates some of the uncertainties associated with AASHTO's recommended method of compaction used for type 1 soils. Based on the weight and consistent compacted thickness of each layer, the density may accurately be achieved. The first layer of soil was weighed and placed in the mold.

The compaction plate was placed in the mold and vibrated until the proper thickness was achieved. The following four layers were compacted in the same manner. Compaction of the final layer and placement of the top platen was critical in the specimen preparation process. It is imperative to ensure an intimate contact between the platens and the specimen. In many cases where the total surface area of the top platen is not utilized, excessive deformations may occur resulting in incorrect measurements of resilient modulus.

After final compaction and placement of top platen, the compaction mold was removed. A vacuum was the applied to the specimen to check for leaks and to ensure integrity of the sample during placement of the acrylic chamber and top plate. Since the specimen is compacted in the membrane, tiny holes may develop during compaction. For this reason, air was used instead of water as the confining medium during testing. If water were used, the degree of saturation would increase thereby causing reduction in modulus or even failure of specimen.

The resilient modulus tests were conducted according to AASHTO Designation TP46-94 Standard Test Method for Determining the Resilient Modulus of Soils and Aggregate Materials. The results of the comparison of resilient modulus tests at maximum density for bulk stresses of

144.7 kPa and 344.7 kPa are shown in Table 6. The US Route 1 RAP yielded resilient modulus values 81 % and 66% higher than the DGA at those stresses, respectively. The Trap Rock RAP yielded resilient modulus values 23% higher than the DGA at a bulk stress of 144.7 kPa and the same resilient modulus at a bulk stress of 344.7 kPa. In general, RAP exhibited higher resilient modulus at lower relative densities as compared to DGA. Recycled concrete aggregate yielded a resilient modulus of 13% higher at both bulk stress of 144.7 and 344.8 kPa.

The results of the comparison of resilient modulus at various bulk stresses are shown in Figure 3. The resilient modulus of all materials increases as the bulk stress increases. The US Route 1 RAP has a higher resilient modulus which may be attributed to the coarser gradation.

The results of the comparison of the permanent deformation is shown in Figure 4 for tests over 100,000 cycles at a deviatoric stress of 310 kPa and confining stress of 103 kPa. The US Route 1 RAP and Trap Rock RAP had average permanent deformations of 16.5 mm . The RCA had a permanent deformation of 1.1 mm, the DGA Blend had a permanent deformation of 2.1 mm, and the DGA had a permanent deformation of approximately 2 mm. Although both RAP samples have a higher resilient modulus than either RCA or DGA, the permanent strains were much higher. The average of the RAP samples showed permanent strains of 780% higher than DGA at 100,000 cycles, while RCA exhibited permanent strains 43% lower than DGA. During the cyclic loading, debonding is believed to occur between the aggregate and asphalt binder, therefore reorienting these particles causing large permanent deformations. Permanent deformation may also be attributed to the plastic deformation of the asphalt binder.

Table 6. Comparison of resilient modulus tests at maximum density.

Material	Mr @ Bulk Stress 144.7 kPa (Mpa)	Mr. @ Bulk Stress 344.7 kPa (Mpa)
RAP - US Route 1	260.25	362.45
RAP - Trap Rock	176.88	217.04
DGA	143.07	217.28
Blend 75% DGA/25% RAP	183.00	274.20
RC A	162.83	245.24

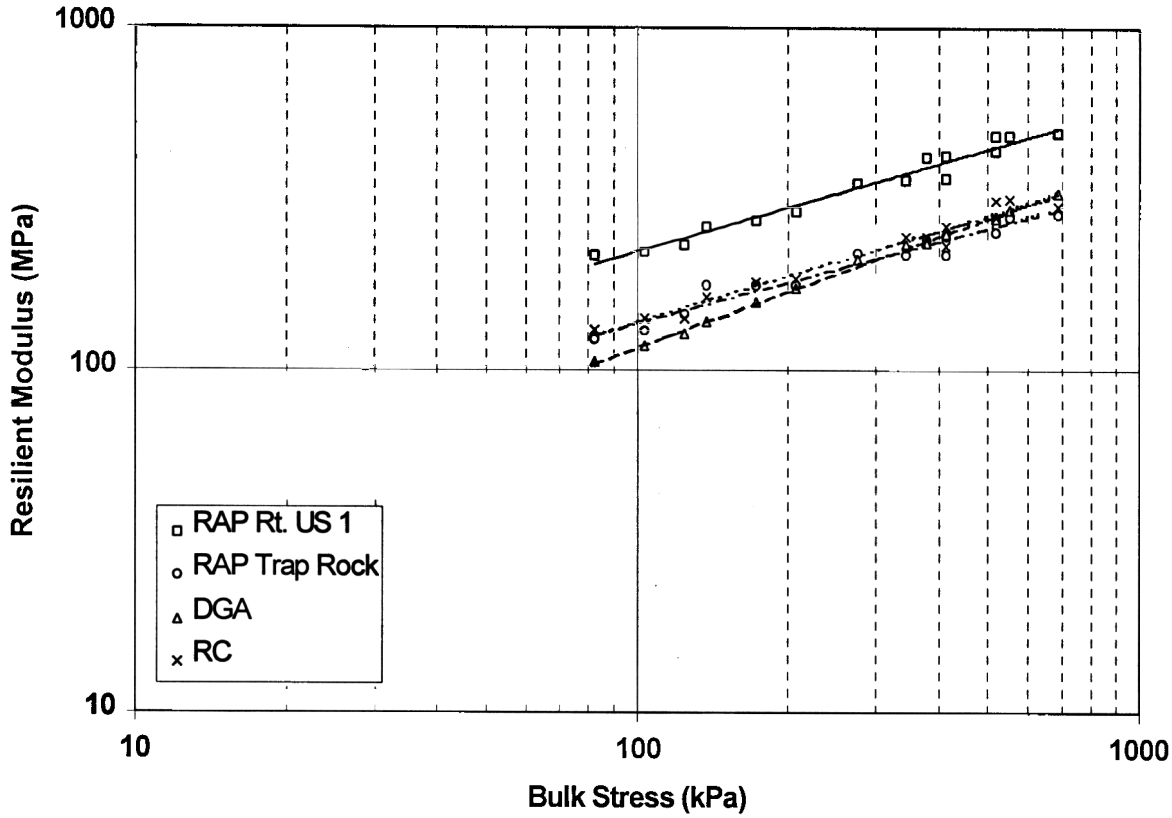


Figure 3. Comparison of resilient modulus data.

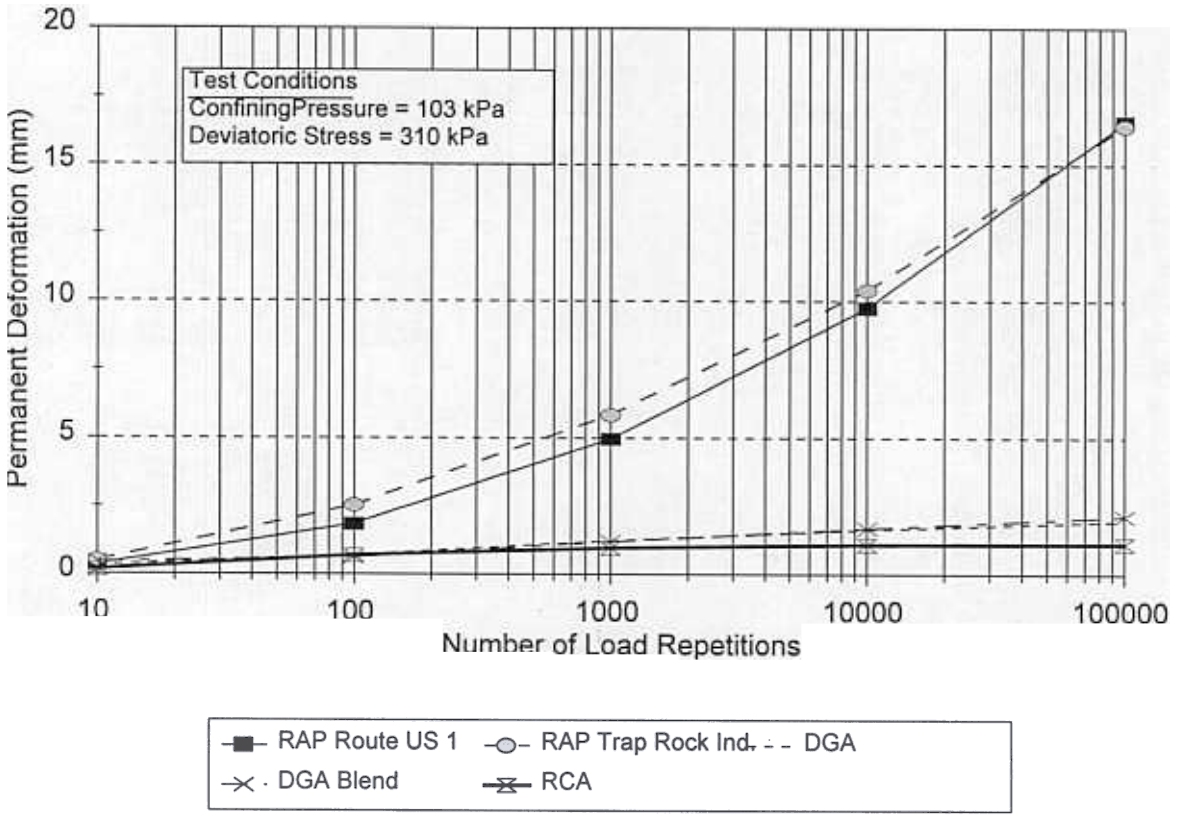


Figure 4. Comparison of two sources of reclaimed asphalt pavement (RAP), dense graded aggregate (DGA), recycled concrete aggregate (RCA) and the blend of 75% DGA and 25% RAP

FIELD TESTING

The Reclaimed Asphalt Pavement was constructed in four dense graded aggregate base course projects to evaluate the construction process, and the pavement performance for a three year period. The evaluation of the construction process included gradation analysis, moisture density measurements and compaction monitoring. The pavement performance data includes Heavy Weight Deflectometer, Seismic Pavement Analyzer and ARAN rut depth measurements.

Route US 206, Bedminister, NJ

The initial shoulder reconstruction project of RAP base course was constructed on Route 206 in Bedminister, NJ in July 1991 by maintenance forces. The project is located between Lamington Avenue and Holland Avenue. The route is a rural two lane undivided highway with moderate traffic.

The RAP base course was constructed in three 1450 meter test sections with three base course thicknesses: (1) 178 mm thickness, (2) 228 mm thickness, and (3) 152 mm thickness. The base course was overlaid with 125 mm of bituminous surface course.

The RAP base gradation analysis is shown in Table 7. The density of the RAP material was 1885.7 kg/m^3. Due to the coarse nature of the material, uniform compaction was difficult to achieve.

The deflection tests were conducted with a Falling Weight Deflectometer with a 4.1 Mg load. The back calculated resilient modulus of the RAP base course was 75 MPa. Initial observations of the shoulder indicated that the pavement had no cracks or other deterioration.

Table 7. Gradation Analysis of Route US 206 Shoulder RAP base course.

Sieve Size	RAP Specification	DGABC Specification	Route US 206 RAP Base Course
50 mm	100		100
37.5 mm	85 - 100	100	93
19 mm	55 - 90	55 - 90	71
4.75 mm	25 - 60	25 - 60	28
300 μm	3 - 25	5- 25	1
75 μm	0 -10	3 - 12	<1

Route US 46, Fort Lee, NJ

The second shoulder reconstruction project of RAP base course was constructed on US Route 46 Section 16P, Fort Lee, NJ in June 1993 under an FHWA contract. The route is an urban four lane divided highway with moderate traffic. The project consisted of four test sections of 92 meters each. The shoulder sections consist of 165 mm of bituminous concrete surface course and 114 mm of the experimental base courses. The four base course test sections were constructed with: (1) 100% virgin dense graded aggregate base course (DGA), (2) 100% reclaimed asphalt pavement (RAP), (3) recycled concrete aggregate (RCA) with 20% RAP, and (4) recycled concrete aggregate with 10 % RAP.

The gradation analysis is shown in Table 8. The Proctor densities were: (1) 2115.9 kg/m^3 for 100% virgin dense graded aggregate base course, (2) 2027.9 kg/m^3 for the 100% reclaimed asphalt pavement, (3) 1931.8 kg/m^3 recycled concrete aggregate with 20% RAP, and (4) 2099.9 kg/m^3 recycled concrete aggregate with 10 % RAP. The source of the material was Stone Industries, Haledon, New Jersey. An Ingersoll Rand 10 ton vibratory compactor was used on all sections.

Heavy Weight Deflectometer.

The Heavy Weight Deflectometer testing was performed by SWK Pavement Engineers, Millington, New Jersey. The deflectometer tests were conducted at 10 meter intervals on each test section in 1994, 1995 and 1996. The load on the 300 mm diameter platen was 1,100 kPa which provided an impact force of 7.9 Mg. Using the PADAL computer program, the deflection data was back-analyzed to determine the effective layer stiffness for the pavement structure. A non-linear model is used in the program to describe the soil response and calculate the stiffness modulus. The mainline pavement and shoulder were overlaid with a 50 mm surface course in 1995. The back calculated stiffness values are shown in Table 9.

The test results indicate that the mean stiffness of the dense graded aggregate and RAP base course are within the normal mean stiffness values for dense graded aggregate base course.

Table 8. Gradation Analysis of Route US 46 Experimental RAP & RCA base course.

Sieve Size	RAP Specification	DGABC Specification	100% DGA	100% RAP	RCA & 20% RAP	RCA & 10% RAP
50 mm	100					
37.5 mm	85 - 100	100	100	100	100	100
19 mm	55 - 90	55 - 90	89	89	87	86
4.75 mm	25 - 60	25 - 60	46	46	40	51
300 µm	3 - 25	5- 25	13	6	10	18
75 µm	0 -10	3 - 12	7.6	1.0	3.7	7.1

Table 9. Comparison of the effective stiffness of the US Route 46 test sections.

	Stiffness Modulus (MPa)			
	DGA	RCA/DGA w/10% RAP	RCA/DGA w/20% RAP	100% RAP
Mean	264	268	478	449
Standard Deviation	269	238	290	286

Cedar Lane Extension

The first mainline pavement project (5) was constructed on the Cedar Lane Extension, Edison Township, Middlesex County in 1993. The project is located between Cedar Lane in Highland Park to Kilmer Road in Edison. This route is a suburban four lane undivided pavement in the Rutgers University campus and light industrial area with an approximate AADT of 10,000 vehicles (low traffic). The contractor of this Local Aid project was Haskell Excavating Company. The NJDOT's Bureau of Materials and the Middlesex County Engineer's office tested the RAP millings. The RAP source was the millings stockpile from the contractor. The dense graded aggregate source was Trap Rock Industries, Kingston, NJ. The samples for sieve analysis and proctor moisture density relationship analysis were taken from the contractor's storage yard, on site before compaction and on site after compaction.

Gradation Analysis.

The gradation analysis for the Cedar Lane project is shown in Table 10. The grain size distribution is consistent, being fine on the 37.5 mm sieve and coarse on the 300 μm and 75 μm sieves. The amount passing the 300 μm sieve failed the dense graded aggregate base course, and the RAP gradation requirements.

The project consists of a 1250 meter test section of 100% RAP base course and a 185 meter test section of dense graded aggregate base course. Both base courses were 200 mm thick. The base courses were overlaid with 280 mm of bituminous surface course and bituminous stabilized base course.

The initial material which was supplied by the contractor for the job, was oversized RAP millings. The oversized RAP was than prescreened to obtain a minus 50 mm size. The roller pattern for compaction was established with both the Troxler Model 3440 Moisture Density Gauge which is normally used for testing soil aggregates, and the Troxler Model 4640B Thin Lift Gauge normally used to test asphalt pavements. The density measurements were taken in the back scatter/surface voids mode for the Model 3440 and 4640B gauges, respectively. Based on the test results, two passes of the roller were selected for maximum density. The density testing was conducted after placement and compaction utilizing both gauges. The measurements were taken at the surface, 50 mm depth, and 100 mm depth.

Table 10. Reclaimed Asphalt Pavement Test Results of the Cedar Lane Project

Sieve Size	Stockpile	Test Strip Before Comp.	Test Strip After Comp.	Final Roadway Samples After Compaction #1	#2	#3	#4	DGABC Spec	RAP Spec.
			Sieve Analysis - dry sieving (percent passing)						
50 mm		100							100
37.5 mm	100	98	100	100	100	100	100	100	85 - 100
19 mm	92	92	89	83	91	92	90	55 - 90	55 - 90
4.75 mm	50	48	45	51	42	49	49	25 - 60	25 - 60
300 µm	5	5	6	6	5	5	6	5 - 25	3 -25
75 µm	1.6	1.0	1.2	3.0	3.0	0.4	0.6	3 - 12	0 - 10

Density Analysis.

The density analysis was conducted on samples as noted above and are shown in Table 11. The optimum moisture content and the maximum dry density were determined by the standard proctor and in-place nuclear densities (Model 3440). The results were similar: 7.0%/ 1874.1 kg/m^3 and 6.8%/ 1858.1 kg/m^3, respectively. The thin lift gauge data was highly variable and inconsistent with those results from the moisture-density gauge and proctor analysis.

The control test section of the standard dense graded aggregate base course, approximately 3400 m^2, was constructed at the end of the project. The optimum number of roller passes was established at three. The dense graded aggregate base course test results are shown in Table 12.

Table 11. Density Analysis

Gauge		Roller Test Strip - Number of passes (kg/m³)						
			#1	#2	#3	#4		
Model 3440		Wet	2082	2098	2114	2098		
		Dry	1938	1954	1954	1938		
		Moisture (%)	7.4	7.6	7.7	7.9		
Model 4640B		Wet	2195	2227	2211	2227		
		Final Roadway Samples (kg/m³)						
Model 3440		#1	#2	#3	#4	#5	#6	Average
Surface	Wet	1938	1954	1986	2082			
	Dry	1810	1842	1874	1954			
	Moist. (%) 7.08	6.09	5.98	6.56	9.09			
Depth								
@50 mm	Wet	1986	1936	1986	1954	1906	2018	1965
	Dry	1858	1826	1858	1826	1762	1922	1842
	Moist. (%) 6.90	6.14	6.90	7.02	8.18	5.00	6.69	
Depth								
@100 mm	Wet	2050	2002	1922	2034	2018	2018	2008
	Dry	1922	1890	1810	1906	1906	1922	1893
	Moist. (%) 6.67	5.93	6.19	6.72	5.88	5.00	6.07	
		Final Roadway Samples (kg/m³)						
Model 4640		#1	#2	#3	#4	#5	#6	Average
Surface	Wet	2371	2307	2467	2371	2275	2467	2376
Depth								
@50 mm	Wet	1506	1762	1842	1698	1586	1826	1703
Depth								
@100 mm	Wet	1602	1810	1794	1810	1698	1794	1751
		Proctor Moisture - density Relationship (kg/m³)						
Density	Original Moisture (%)	Moisture Content(%)						
	3.5%	0	2.1	3.5	6.3	7.0	7.8	8.5
Wet	1906	1714	1858	1874	1922	2002	2002	1954
Dry	1842	1714	1826	1810	1810	1874	1858	1810

Table 12. Dense Graded Aggregate Test Results for Cedar Lane Extension

Sieve Size	DGA Specification	Jobsite Stockpile	Quarry Stockpile
	Sieve Analysis (% Passing)		
	100	100	100
	85 - 100	84	76
	55 - 90	44	39
	25 - 60	13	18
	3 - 12	9	10

	Density Analysis - Final Roadway Samples					
	#1	#2	#3	#4	#5	#6
Wet	2372	2374	2372	2372		
Dry	2171	2190	2171	2150		
% Moist	9.3	8.8	9.1	10.4		

Heavy Weight Deflectometer.

The Heavy Weight Deflectometer testing was performed by SWK Pavement Engineers, Millington, New Jersey. The Heavy Weight Deflectometer uses a load pulse to resemble moving traffic loads. The seven pavement surface deflections are recorded at an increasing radial distance from the impact force. The tests were conducted with an impact force of 47.86 kN on a platen of 300 mm diameter and applied stress of 680 kPa. A total of 90 tests were conducted at 20 m spacing in the southbound and northbound lanes.

Using the PADAL computer program, the deflection data was back-analyzed to determine the effective layer stiffness for the pavement structure. The average stiffness modulus is shown in Table 13. The stiffness results indicate that the RAP base course is stiffer than the dense graded material.

Table 13. Effective stiffness of dense graded aggregate and RAP base Course of Cedar Lane Extension

Direction	Stiffness Modulus (MPa)	
	DGABC	RAP Base Course
Southbound	78	114
Northbound	103	126
Wt. Average	86	138

Rut Depth Data

Pavement rutting is the result of permanent deformation in the pavement layers. It is usually caused by material consolidation of the pavement layers or plastic movement of the bituminous layers. The rut depth measurements were completed with a 1995 Automatic Road Analyzer (ARAN) Model 6900.

The Rut Depth Data is shown in Table 14. The average rut depths of all lanes of both the RAP base course and the dense graded aggregate base course are similar, except the rut depths of the right eastbound lanes which are statistically significant. The standard t-test of the means indicates that the rutting in the test section of the dense graded base course is higher than the test section of the RAP base course. At this location, the right eastbound lane may have higher traffic due to the entrance to a parking lot.

Table 14. Rut Depth Data of Cedar Lane Test Sections

	Test Sections			
	Reclaimed Asphalt Pavement (mm)		Dense Graded Aggregate (mm)	
Lane	Average	Standard Dev.	Average	Standard Dev.
Right (Westbound)	2.81	1.16	3.00	1.00
Left (Westbound)	2.87	1.16	2.74	1.00
Right (Eastbound)	3.04	1.24	4.34	2.74
Left (Eastbound)	3.16	1.68	3.12	1.34

US Route 1, Section 5G & 6U, New Brunswick, NJ

The US Route 1, Section 5G & 6U, reconstruction project included right lane and shoulder widening. The pavement is a 6 lane divided highway in a suburban shopping area with an approximate AADT of 60,000 vehicles (medium traffic) with 7 - 10% heavy trucks. The three 150 meter test sections were constructed with 100% RAP base course, standard dense graded aggregate base course and a blend of 75% dense graded aggregate and 25 % RAP base course in the outside lane and shoulder widening in June 1994. The base courses were covered with a total of 228 mm of bituminous surface course and stabilized base course. The test sections are located in the southbound lanes between the North Brunswick Shopping Center and the off ramp to Livingston Avenue. The general contractor was George Harms Construction Company. The RAP source was an approved job site stockpile. The source of the dense graded aggregate and the blend was approved materials from Trap Rock Industries.

Gradation Analysis.

Subsequent to the construction of the US Route 1 test sections, the NJDOT adopted a revised gradation specification for the use of RAP in dense graded aggregate base course. To test the revised gradation, three comparison test (6) were performed on the RAP and blended 75% DGA and 25% RAP base course materials:

- Comparison of the gradations between washed and unwashed samples was performed with AASHTO T-27. During the compliance testing, an additional gradation was performed without the wash step. The results are shown in Table 15.

  Comparison of gradations between air drying and low temperature hot plate drying was performed with AASHTO T-27. Samples of RAP and the blend were split; one half was air dried (one aggregate layer thick); and one half was dried on a low heat hot plate at 60 degrees Centigrade. The results are shown in Table 16.

Gradation of RAP using four different drying methods was performed with AASHTO T-27. Three samples were taken of RAP from the contractor's stockpile. Each sample was split into four portions and each portion was graded with the following drying methods: (1) air dried and washed, (2) hot plate dried and washed, (3) hot plate dried and unwashed, and (4) air dried and unwashed. The test was performed to determine the optimal drying method for RAP. The results are shown in Table 17.

Table 15. Comparison of the gradations between washed and unwashed samples of the Blend 75% DGA/25%RAP

Sieve Size	RAP Gradation Specification	DGA Gradation Specification	Blend 75%DGA/25%RAP		100% RAP	
			Washed	Unwashed	Washed	Unwashed
50 mm 100		100	100	100	100	
37.5 mm	85 - 100	100	100	100	100	100
19.0 mm	55 - 90	55 - 90	77	77	94	93
4.75 mm	25 - 60	25 - 60	43	36	54	50
300 µm	3 - 25	5 - 25	10	3	2.9	2.4
75 µm	0 - 10	3 - 12	4.6	0.3	1.6	0.1

Table 16. Comparison of the gradations between air drying and low temperature hot plate drying of the blend 75%DGA/25% RAP and 100% RAP

Sieve Size	RAP Gradation Specification	DGA Gradation Specification	Blend 75%DGA/25%RAP		100% RAP	
			Air dried	Hot plate dried	Air dried	Hot plate dried
50 mm 100		100	100	100	100	
37.5 mm	85 - 100	100	100	100	100	100
19.0 mm	55 - 90	55 - 90	83	80	84	88
4.75 mm	25 - 60	25 - 60	44	41	44	44
300 µm	3 - 25	5 - 25	18	12	7	2
75 µm	0 - 10	3 - 12	10	7	2	0.2

Table 17. Comparison of the RAP gradations using four different gradation methods

Sieve Size	RAP Gradation Specification	DGA Gradation Specification	RAP Samples Air dried washed	Hot plate dried washed	Air dried unwashed	Hot plate dried unwashed
50 mm 100		100		100	100	100
37.5 mm	85 - 100	100	100	100	100	100
19.0 mm	55 - 90	55 - 90	92	92	93	91
4.75 mm	25 - 60	25 - 60	49	49	48	43
300 µm	3 - 25	5 - 25	11	2	3	1
75 µm	0 - 10	3 - 12	5		0	0

Density Analysis.

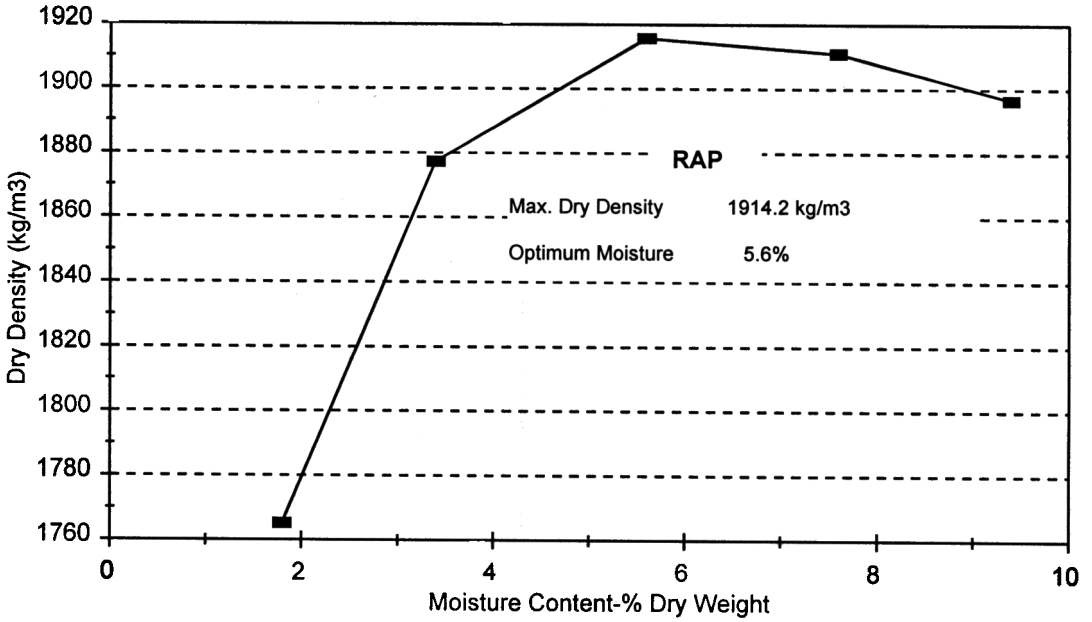
Two comparison tests (6) were performed on the RAP and blended 75% DGA and 25% RAP base course materials to determine moisture - density relationships:

Comparison of moisture content was performed between the field nuclear density gauge and the hot plate method. As field density testing was performed with the nuclear gauge, material samples were taken from the density test locations and hot plate moisture tests were run immediately upon returning to the field laboratory. The results are shown in Table 18.

Comparison of the moisture-density relationship was performed between Blend 75% DGA/25% RAP and RAP using the AASHTO T-99 Method C with the replacement option for each material in the project. The results are shown in Figure 5.

Table 18. Comparison of moisture-density relationship between the field nuclear density gauge and the hot plate method.

	Density Analysis	
Density Test	Blend 75%DGA/25%RAP	RAP Base Course
Average Field Moisture (%)	4.2	6.7
Average Hot Plate Moisture (%)	2.9	3.5
Maximum Dry Density (kg/m^3)	2210.5	1915.8
Optimum Moisture (%)	7.6	5.5



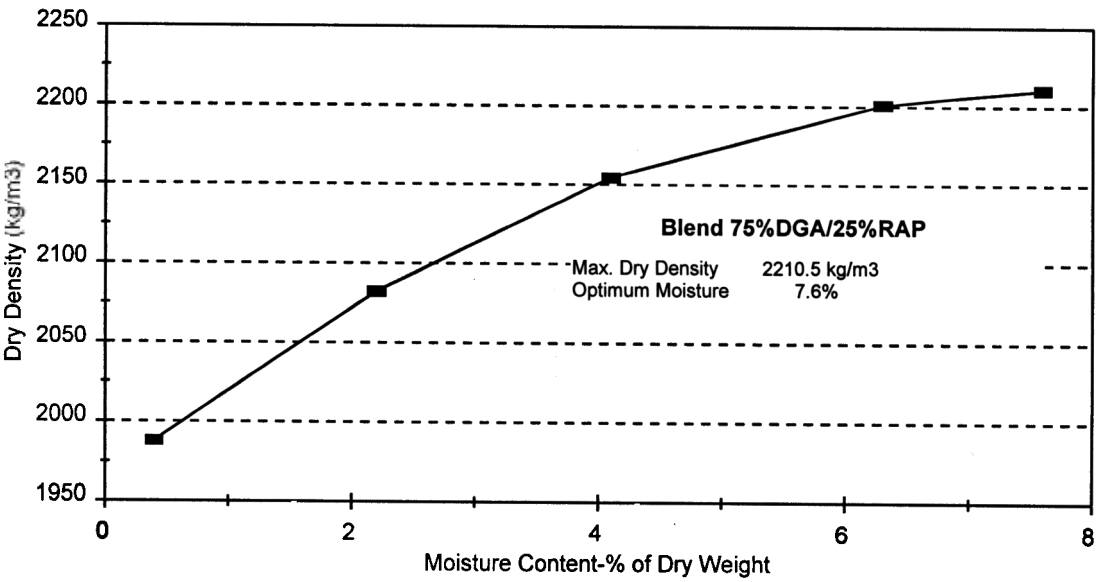


Figure 5. Moisture Density Relationship between RAP and 75%DGA/25%RAP Blend

Heavy Weight Deflectometer.

The Heavy Weight Deflectometer testing was performed by SWK Pavement Engineers, Millington, New Jersey. The Heavy Weight Deflectometer test parameters were similar to the Cedar Lane tests above. A total of 48 tests were conducted in the outside lane and shoulder of the three test sections.

Using the PADAL computer program, the deflection data was back-analyzed to determine the effective layer stiffness for the pavement structure. The average stiffness modulus is shown in Table 19. The stiffness results indicate that the RAP base course is stiffer than the dense graded aggregate.

Table 19. Effective stiffness of DGA, Blend 75%DGA/25%RAP, and RAP base course. Heavy Weight Deflectometer

Test Section	Stiffness Modulus (MPa)		
	DGA	Blend 75%DGA/25%RAP	RAP
Right Lane	90	437	591
Shoulder	325	631	698

Seismic Pavement Analyzer.

A pavement evaluation was performed using a Seismic Pavement Analyzer (SPA), which is a nondestructive testing device for analyzing the condition of the pavement through evaluation of material properties, thickness of individual courses, and detection of distress precursors. The elements being evaluated include:

Elastic moduli and thickness of pavement layers

Overlay delamination

Presence of voids or loss of support below rigid pavements

Fine cracking in an asphalt-concrete overlay

Presence of moisture in the subgrade. In concept, the device is very similar to the Falling Weight Deflectometer (FWD). The device utilizes three nondestructive seismic methods:

Spectral-Analysis-of-Surface-Waves (SASW) method is primarily used for evaluation of layer moduli and thickness,

Impact Echo (IE) method for evaluation of the surface layer thickness and overlay delamination,

Impulse Response (IR) method detects voids and loss of support below rigid pavements, and presence of moisture in the subgrade, etc.

Ultrasonic Compression Wave

Ultrasonic Surface-Wave

The primary objective of the testing was to evaluate the thickness and elastic moduli of all the courses, and the damping ratio of the pavement system. The thickness of individual courses was evaluated by the SASW method. In addition, the combined thickness of the

bituminous surface and base courses was evaluated by the ultrasonic compression wave and impact echo methods.

The Young's moduli for the base courses are presented in Table 20. The average moduli for RAP, RAP/DGA blend and DGA sections are of comparable magnitude. While the average modulus for the right lane base courses is somewhat lower than the moduli for the shoulder base courses. The back calculation of the base course moduli depends on the calculation of the moduli and thickness of the surface and subbase courses. The combined thickness of the top two bituminous surface and base courses compared very well to the combined design thickness, with an average error of only about 7% as measured by the SASW test and 18% as measured by the impact echo test. The thickness of the DGA measured by the SASW test overestimates the design thickness, on average by about 35%. As expected, there are no significant differences in moduli of bituminous layers for the three sections.

Finally, the damping ratio of the pavement system was measured using the impulse response technique. The damping ratio is an indicator of the degree of resistance to movement of the surface course. It is more often used in detection of voids and loss of support below rigid pavements, that are characterized by a lightly damped behavior. The 100% RAP and the blend respectively exhibit a higher degree of damping than DGA base course.

Table 20. Young's moduli of DGA, Blend 75%DGA/25%RAP, and RAP base course. Seismic Pavement Analyzer

	Stiffness Modulus (MPa)		
Test Section	DGA	Blend 75%DGA/25%RAP	RAP
Right Lane	11,500	11,100	11,600
Shoulder	9,800	10,200	9,700

Rut Depth Data

The rut depth measurements were completed with the 1995 Automatic Road Analyzer (ARAN) Model 6900.

The Rut Depth Data is shown in Table 21. The average rut depths of the outside lanes of the RAP base course, the dense graded aggregate base course, and the blend of 75% DGA/ 25% RAP are similar. The standard t-test of the means of two normal populations with equal standard deviations using independent samples indicates that the rutting of the three test sections are not significantly different.

Table 21. Rut Depth data for US Route 1

Right Lane					
Dense Graded Aggregate		Reclaimed Asphalt Pavement		Blend 75% DGA/25% RAP	
Average (mm)	Stand. Dev (mm)	Average (mm)	Stand. Dev (mm)	Average (mm)	Stand. Dev (mm)
1.10	0.55	1.44	0.70	1.41	0.80

SUMMARY & CONCLUSIONS

This report documents the laboratory and field study of reclaimed asphalt pavement and recycled concrete aggregate for use in base course. The study was conducted to confirm the recently adopted RAP specifications, and investigates the engineering properties such as gradation, degradation, resilient modulus and permanent deformation of RAP, RCA and blended 75% dense graded aggregate with 25 % RAP, and compares these properties with DGA. Four base course projects with RAP, RAP/DGA blend, and DGA for comparison were constructed to investigate and confirm the constructability, density, and rutting potential. The use of 100% RAP base course in-place of dense graded aggregate is confirmed for low and medium traffic pavements. Since RCA has been used successfully for several years as base course, no test projects were constructed to confirm the use of RCA base course. The use of RAP/DGA blend is also confirmed for use in base course.

The literature search indicates the effectiveness of RAP and RCA as a substitute material in base course. Resilient modulus, and CBR tests indicate that the stiffness modulus properties of RAP and RCA are at least equal to dense graded aggregate. However, permanent deformation properties indicate a potential for increased rutting over the dense graded aggregate.

The laboratory and field testing gradation analysis indicates the non-uniformity of RAP samples from stockpiled materials which are generated from the milling process. To achieve compaction and density, RAP with material size above 50 mm must be removed or ground to size. RAP passing the 75 μm and 300 μm sieves appears to be less significant to the compaction and density process since tests indicate that the RAP degrades during compaction. This degradation during compaction is attributed to the debonding of the aggregates from the asphalt

binder and re-orientation of these particles during compaction. The gradation analysis of two RAP base course shoulder projects and two RAP mainline pavement projects further show the variability of RAP gradations.

Accelerated drying tests were conducted on RAP samples to develop a procedure to reduce drying time for the gradation testing. Although the tests indicated that the air drying and oven drying produced significantly different gradations on the 300 mm and 75 mm sieves, the overall significance and effect of the gradation on the quality of the material was not established for eliminating the use of the oven drying.

The CBR results show a large variability between the methods and a large variability between the samples within each method. The variability of CBR values for the AASHTO method may be affected by the debonding of the grains from the asphalt binder. In the NJDOT method, the high values may be attributed to the compaction by static loading which compacts samples to densities above the maximum density. The CBR values for the RAP samples are somewhat lower than the values for the DGA and RCA.

The resilient modulus tests indicate that RAP, the RCA and Blended DGA/RAP materials have somewhat higher values or at least similar values to DGA. Resilient modulus is an index that describes the nonlinear stress-strain behavior of soils under repeated loads, and provides values for determining layer thickness and the overall system response due to traffic loads for mechanistic design procedures. The resilient modulus values indicate that the RAP, RCA and Blend can be substituted for DGA of similar thickness in a mechanistic design system. Deflection testing on base course test section indicates that RAP has higher stiffness modulus

values than the DGA which is consistent with the higher laboratory resilient modulus values of RAP materials.

The permanent deformation tests indicate that the RAP in considerably more susceptible to rutting than either the DGA, RCA or the Blend. This test finding is consistent with other tests from other agencies. However, when RAP was used in base course projects, the rutting was not evident from the rutting measurements. The RAP on the Cedar Lane Extension project with light urban traffic indicated similar rutting to the DGA base course section, and the RAP on the US Route 1 with medium traffic, also indicated similar rutting to the DGA base course section. The use of RAP base course needs to be established for pavements with heavy traffic loads where the rutting potential is high.

To test the revised RAP specification, comparisons tests were initiated for gradations between washed and unwashed samples, between air drying and low temperature hot plate drying, and a comparison of four different drying schemes. Comparison tests were also performed for of moisture content between field nuclear density and hot plate methods. The tests confirmed the provisions of NJDOT Specification A-10, Determination of Gradation of Dense Graded Aggregate Containing Reclaimed Asphalt Pavement which requires wet sieving and oven drying.

RECOMMENDATIONS

The use of 100% RAP base course and RAP/DGA blend base course in-place of dense graded aggregate is recommended for low and medium traffic pavements where severe rutting is not anticipated. In addition to the consideration for the potential of severe rutting, the pavement designer should consider traffic loading in the design of RAP base courses. The specification 908.18, Dense Graded Aggregate, and A-10, Determination of Gradation of Dense-graded Aggregate Containing Reclaimed Asphalt Pavement should be used for the construction of RAP base course.

2. Since RCA has been used successfully for several years as base course, the continued use of RCA base course in-place of dense graded aggregate is confirmed.

REFERENCES

O'Mahony, M. M., and G. W. E. Milligan. Use of Recycled Materials in subbase Layers. In *Transportation Research Record* 1310, TRB, National Research Council, Washington, D.C., 1991.pp. 73 - 80.

2. Barksdale, Richard D., Samir Y. Itani and Terry E. Swor. Evaluation of Recycled Concrete, Open-Graded Aggregate, and Large Top Size Aggregate Bases. In *Transportation Research Record* 1345, TRB, National Research Council, Washington, D.C., 1992 .pp. 92 - 100.

3. Davis, Jeffery S., Milton T. Huston, and K. Wayne Lee. *Structural Analysis of New England Subbase Materials and Structures,* Town of Narragansett, Narragansett, RI, 1997.

4. Garg, Navneet, and Marshall R. Thompson, Lincoln Avenue Reclaimed Asphalt Pavement Base Project. In *Transportation Research Record* 1547, TRB, National Research Council, Washington, D.C., 1996.

5. Palise, Frank. *Laboratory Investigation 92-2: Performance Evaluation of Reclaimed Asphalt Pavement and Dense Graded Aggregate Base Course*, New Jersey Department of Transportation, Trenton, NJ. January 1994.

6. Qureshi, Ahmand. *Continuing Performance Evaluation of RAP as DGABC on Route 1 Section 5G & 6U Project.* New Jersey Department of Transportation, Trenton, NJ. December 1994.

APPENDIX A

NEW JERSEY DEPARTMENT OF TRANSPORTATION STANDARD SPECIFICATION

901.08 Dense-Graded Aggregate.

Dense-graded aggregate shall consist of broken stone conforming to Subsection 901.04, crushed gravel conforming to Subsection 901.05, or blast furnace slag conforming to Subsection 901.06, except that at least 90 percent of all fragments shall contain at least one face resulting from fracture, and shall conform to the following requirements and gradation:

1. The moisture content of dense-graded aggregate immediately prior to placement shall be 6 ± 2 percent based on dry weight. If dense-graded aggregate is to be paid for on a weight basis, the moisture content shall not exceed eight percent when delivered to the Project.

Sieve Size	Percent Passing
37.5 mm	100
19.0 mm	55 - 90
4.75 mm	25 - 60
300 μm	5 - 25
75 μm	3 - 12

2. When tested in accordance with AASHTO T 90, the portion passing the 425-micrometer sieve shall be nonplastic.

Dense-graded aggregate may be produced from recycled concrete aggregate which shall conform to the gradation and plasticity requirements above and to the following:

1. Composition.

	Percent by Weight	
	Minimum	**Maximum**
Portland cement concrete	90 (Note 1)	
Bituminous concrete		10 (Note 2)
Brick, mica, schist, and other friable material		4 (Note 2)
Reactive material		0
Wood		0.1 (Note 2)

Note 1: In order to meet the minimum requirement, broken stone, crushed gravel, or crushed vitreous china may be added. Broken stone shall conform to Subsection 901.04. Crushed gravel shall conform to Subsection 901.05, except that it need not be washed. Crushed vitreous china shall conform to the requirements for resistance to abrasion and soundness listed in this Section.

Note 2: The percent shall be determined by separating the material retained on the 4.75-millimeter sieve and expressing that amount as a percentage of the total weight of material retained on the 4.75-millimeter sieve.

2. Resistance to Abrasion. The loss shall not exceed 50 percent when tested in accordance with AASHTO T 96 (Los Angeles Machine).
3. Soundness. The loss shall not exceed 15.0 percent when tested in accordance with AASHTO T 104 by the use of sodium sulfate.
4. Prior to use, test results certifying compliance to the above requirements shall be submitted to and verified by the Department Laboratory.
5. A quality control plan shall also be submitted for approval and shall include the following:
    a. The assignment of quality control responsibility to specifically named individuals.
    b. Performance of regularly scheduled inspection procedures including inspection of the source concrete for the recycled concrete aggregate.
    c. Provisions for the prompt implementation of control and corrective measures.
    d. Provisions for liaison with the Engineer at all times.
    e. Performance of necessary quality control tests.

        The quality control procedure shall include performance of the following tests while stockpiles of recycled concrete aggregate are being produced:

        (1) Gradation. Testing in accordance with AASHTO T 27 and T 11 shall be performed at least once a day.
        (2) Composition. Continuous visual inspection and removal of objectionable material to ensure compliance.
        (3) Soundness of aggregate in accordance with AASHTO T 104 and resistance to degradation in accordance with AASHTO T 96 shall be performed a minimum of once every two weeks.
6. Reporting of Recycled Materials Usage. The Contractor shall report to the Solid Waste Management District of origin, in accordance with NJAC 7:26A, the metric weight of concrete aggregate being recycled. A copy of the reported information shall be provided to the Resident Engineer.

Dense-graded aggregate may also be produced by mixing reclaimed asphalt pavement (RAP) conforming to Subsection 901.10, Subpart B, with previously approved virgin dense-graded aggregate.

The method of mixing shall be such that the blended mixture will be homogeneous with regard to particle size and composition. The percentage of each of the above two components shall be determined by the Contractor and shall conform to the following:

1. Composition.

	Percent by Weight	
	Minimum	**Maximum**
Reclaimed Asphalt Pavement and Virgin Dense-Graded Aggregate	(Notes 2 & 3)	(Notes 2 & 3)
Portland Cement Concrete		5 (Note 2)

Brick, Mica, Schist, and other friable materials	4 (Note 2)
Wood	0.1 (Note 2)

Note 3: The percentage of these two components shall be established by the Contractor. During production these percentages, as measured at the source, shall not vary by more than plus or minus 15 percent from the established value.

2. Plasticity and Gradation. This blended material shall be nonplastic when the portion passing the 425-micrometer sieve is tested in accordance with AASHTO T 90, and shall conform to the following gradation when tested in accordance with Section 990, NJDOT A-10:

Sieve Size	Blended Percent Passing
50 mm	100
37.5 mm	85 - 100
19.0 mm	55 - 90
4.75 mm	25 - 60
300 µm	3 - 25
75 µm	0 - 10

3. The above gradation shall apply only to mixes containing RAP. Mixes comprised of 100 percent virgin material shall conform to Subsection 901.08.
4. Prior to approval, test results certifying compliance with the above requirements shall be submitted to, and verified by, the Department Laboratory.
5. The supplier shall maintain an effective quality control program for gradation and composition.
6. Density control shall conform to Subsection 301.05. When AASHTO T 238 Method B and T 239 (nuclear gauge methods for measuring density and moisture content) are used to perform Compaction Acceptance Testing (Subsection 301.05, Subpart B), a representative sample of five tests for each 4 000-square meter lot will be taken. For the purposes of the Q statistic, each test here is defined as the dry density determined from a field-measured wet density measurement and its corresponding laboratory-measured percent moisture value. This percent moisture value will be determined through the timely transport of a 1 000-gram sample of each field-tested specimen to a laboratory where it will be dried to a constant weight. The percent moisture will be calculated as a function of the weight difference before and after drying. (Notes 4 and 5).

Note 4: For this test procedure only, the term "constant weight" is defined as that weight at which all the moisture (H_20) is driven off prior to any loss of volatile fractions from the asphalt cement.

Note 5: Moisture may be driven from the sample by low temperature oven drying or heating with a hot plate, providing the heating does not affect the gradation of the RAP in the sample.

APPENDIX B

A-10 DETERMINATION OF GRADATION OF DENSE-GRADED AGGREGATE CONTAINING RECLAIMED ASPHALT PAVEMENT (RAP)

A. Scope.

This method of test is used to rapidly determine the gradation of Reclaimed Asphalt Pavement (RAP).

B. Apparatus.

The apparatus will be in accordance with AASHTO T 27.

C. Sample.

The sample will be obtained and reduced in accordance with AASHTO T 2 except that the material need not be dried before splitting.

D. Procedure.

A minimum 5000-gram sample of RAP will be sieved without drying (wet-sieved) through the following sieves: 50-millimeter, 37.5-millimeter, 19.0-millimeter, and 4.75-millimeter. The material passing the 4.75-millimeter sieve will be separated, reduced to 500 grams, spread out in a pan, and put in an oven preheated to 80 ± 3 degrees C for approximately 1.5 hours. The material will be removed from the oven at 15 minute intervals, weighed, and remixed to promote even and thorough drying.

If the dense-graded aggregate (DGA) is 100 percent RAP after drying to a constant weight, the minus 4.75-millimeter material is graded.

If the DGA is a blend of RAP and virgin DGA, the minus 4.75-millimeter material will be washed, dried using the above procedure, and graded.

The gradation results of the plus 4.75-millimeter and minus 4.75-millimeter portions of the material will be combined mathematically for a final gradation.

E. Report.

The report will include the mathematically combined gradation results reported as a total percent passing the required sieves.

Appendix C

CBR Test as Performed by NJDOT

California Bearing Ratio Tests are normally made on subbase subgrade material. Such results are prepared and sent foreword to the Soils Bureau and the Region submitting sample. The results are analyzed for future construction of roads.

There are occasions when material is submitted for CBR tests that is not subbase subgrade material. Results are interpreted as required by the Engineer.

Material is allowed to air dry on floor. After drying, it is prepared for grading. The sample is selected either by quartering or splitting whichever method is most feasible. The sample should weigh approximately 5000 grams. It is washed over a #200 sieve. The sample is then dried to a constant weight in an oven at a temperature of 110 ± 5 degrees C (230 ± 9 degrees F). After drying, the sample shall be separated into a series of sizes using such sieves as required. Normally, these sieves are 4", 2", 3/4", #4. #50 and #200. The results are recorded on the form.

The next step is to perform a moisture density test. This test is made in accordance with AASHTO T-99, Method C.

A 4000 gram sample of the material is prepared by manufacturing it from the original material base. The percentages obtained in the initial grading. Sample is composed of - 3/4" and plus #4 and - #4 material. Mix sample thoroughly with the amount of water as determined above in AASHTO T-99 Method C.

The manufactured sample is then placed in a CBR Mold. Place spacer disk on top of material and compress in compression machine to 56,000 pound pressure on the dial. Measure depth of compressed sample from the top of the mold to the top of the spacer disk. Record on form. Remove spacer disk.

Perform penetration test with 2" diameter piston at 0.1 to 0.5 inch. Read in increments of 0.1 inch. Record pressure from compression machine dial at each .1 inch increment. Depth of penetration is measured by means of an Ames Dial.

The sample in the mold is then turned over and refastened to the plate. Remold sample as above with the spacer disk. Mold at 56,000 pound pressure on the dial. Check height from top of mold to top of spacer disk.

Place designated weight and adjustable stem in the mold with the sample. The weights consist of a perforated plate, a ring approximately ½" thick and a U shaped weight 3/4" thick and an adjustable stem. These will weigh about 12 pounds. Immerse the sample in water to allow free access of water to top and bottom of the specimen. During soaking, maintain water level in the mold and soaking tank approximately 1 inch above top of mold. The water will be at room temperature. Place the tripod with dial detector on top of mold and make initial dial reading. Record this information on form. Soak the specimen 96 hours (4 days). At the end of the 96 hours make final dial reading on the soaked specimen and calculate swell.

Determine bearing value of soils (usually subbase) when compacted at optimum moisture control to varying degrees of density. Good in evaluation of subsoil base course material, - 3/4 inch material.

Remove all weights and vary carefully decant the water in the mold. Do not disturb the specimen.

Perform penetration test again as outlined above. Record the information on form.

Take moisture sample of about 500 grams from specimen. Sample should be taken from the center of the mold. Place in oven to dry. After drying make required calculations.

Report will contain the following information. The report is normally made on Form LB-13. Distribution is to Soils Bureau, the Region that submitted sample and file one copy. On the face of Form

LB-13 record original gradation. There are no grading specifications. All data and calculations are made on locally produced work sheet.

On the reverse side of the LB-13 the remaining information is written:

Expressed as:

1. Approximate maximum dry density P.C.F.
2. Approximate optimum moisture %

California Bearing Ratio

3. Penetration as molded %
1. Penetration after 4 days saturation %
2. Swell after 4 days saturation %
3. Moisture content after 4 days %

Calculations:

Items 1 and 2 as outlined in AASHTO T-99
Item 3

$$\frac{\text{Penetration Value (lbs.) for .1 inch penetration reading}}{\text{Area of Penetrometer}} = \text{lbs./in.}^2$$

$$\frac{\text{lbs./inches}^2}{1000 \text{ lbs./in.}^2 \text{ (Standard)}} \times 100 = \%$$ penetration as molded

If penetration is calculated at 0.2 inch use 1500 lbs./in.^{2} (Standard)

Item 4. Calculated as in Item 3
Item 5. Swell

$$\frac{\text{Final Dial Reading - Initial Dial Reading}}{\text{Remolded Height in Inches}} \times 100 = \%$$ Swell

Item 6. Moisture Content
a - b = c
b - d = e
c/e = f

Where: a. Wt. of can and wet soil
b. Wt. of can and dry soil
c. Wt. loss
d. Wt. of can
e. Wt. of dry soil
f. Moisture